

# TYPES OF RIVER CHANNEL PATTERNS AND THEIR NATURAL CONTROLS

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## ABSTRACT

River channel patterns are thought to form a morphological continuum. This continuum is two-dimensional, defined by plan features of which there are three (straight, meandering, branching), and structural levels of fluvial relief of which there are also three (floodplain, flood channel, low-water channel). Combinations of these three categories define the diversity of patterns. One of the most important factors in channel development is stream power, defined by water discharge and river slope. The greater the stream power, the stronger the branching tendency, but threshold values of stream power are different for the three different hierarchical levels of channel relief. The critical stream power values and hydrological regime together define the channel pattern, and analysis of the pattern type can be undertaken using effective discharge curves. © 1998 John Wiley & Sons, Ltd.

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KEY WORDS: channel pattern; meandering; braiding; anastomosis; continuum concept; effective discharge curve

## INTRODUCTION

Why do rivers have differing channel patterns? This question has attracted the attention of fluvial geomorphologists and river engineers for many years. In 1897, Lokhtin postulated that river forms reflect three main independent factors, namely (1) the discharge regime which depends on climatic and soil conditions; (2) the slope or gradient conditioned by the relief of the area crossed by the river; (3) the erodibility of the bed depending on the sediment properties. These three controls determine features of the river pattern and hydraulic conditions of the flow. Lokhtin offered a channel development criterion, defined as the ratio between the stream power (indexed by the gradient) and the erodibility of the bed (indexed by grain size). Lower values of this criterion correspond with stable sinuous ‘meandering’ rivers, higher ones conform to unstable divided or ‘braided’ streams. A number of similar criteria based both on theoretical and empirical investigations have shown an analogous tendency, but broad transitional conditions are often found.

In 1957, both Leopold and Wolman, and Lane published results of channel pattern analyses using gradient–discharge charts. They demonstrated that braided rivers plot above meandering ones and that discriminant functions may be determined. Straight channels plotted either on both sides of meandering–braided transition (Leopold and Wolman, 1957) or below meandering channels (Ackers and Charlton, 1970; Schumm and Khan, 1972). Later investigations identified various modifications of meandering–braided and straight–meandering discriminant functions. Detailed critical reviews and analyses of these investigations have been given by Carson (1984), Ferguson (1984, 1987), Bridge (1985) and Miller (1988).

Concerning the paper by Leopold and Wolman (1957), Ferguson (1987) pointed out that it is remembered mainly for its use of discrimination and thresholds, in spite of emphasizing a morphological continuum of channel patterns; many intermediate patterns exist, and are the norm rather than exceptions. This concept has been a constant element in investigations of controls of channel pattern (Knighton and Nanson, 1993) and application of the term *total sinuosity* (Richards, 1982; Robertson-Rintoul and Richards, 1993) can be considered as an attempt to make the quantitative analysis of the continuum.

Unfortunately, some works published in Russian have been ignored by the above-mentioned reviews, and in the following section we try to rectify this.

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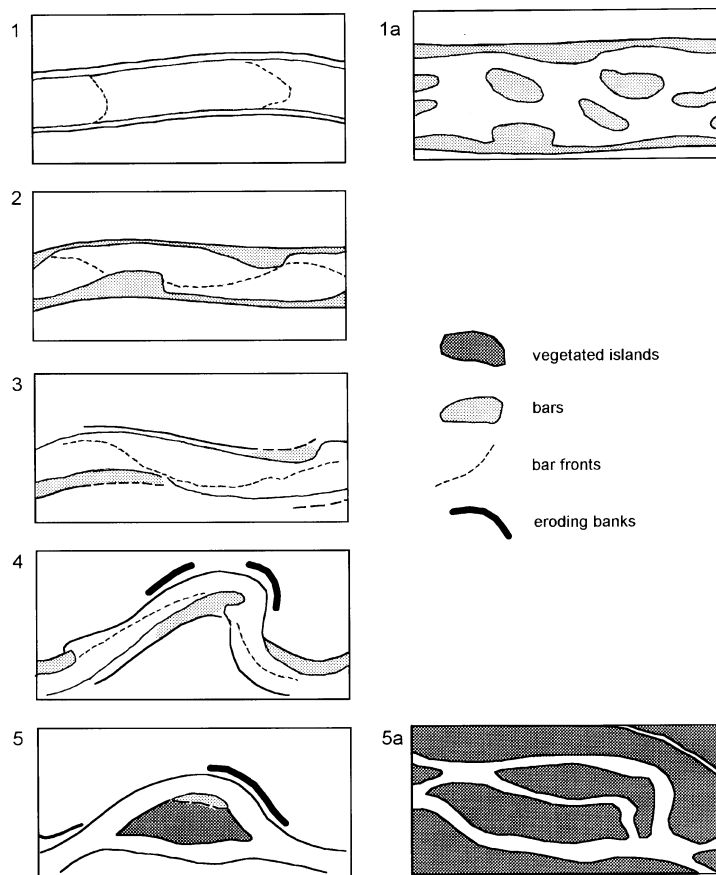


Figure 1. Classification of channel processes by Kondrat'ev *et al.* (1982)

### TERMINOLOGY AND CLASSIFICATION

Original classifications of river channel pattern (Rossinskiy and Kuz'min, 1947; Leopold and Wolman 1957; Andreev and Yaroslavtsev, 1958) discerned three essential types: straight, meandering and braided. Anastomosing, split, wandering, 'meandertal' (meandering talweg) and some other patterns were distinguished later, and were interpreted either as transitional forms or as subtypes. As new types were discerned, new classification schemes were developed. Nowadays the classification of Kellerhals *et al.* (1976) is most detailed, but it appears to be rather complicated.

In the former USSR, the classification developed in The State Hydrological Institute (Kondrat'ev *et al.*, 1982) was considered to be the official standard. This scheme marks out seven types of channel processes (Figure 1, numbered according to the original).

1. *Transverse bar process* – downstream movement of transverse bars separated from each other by four to eight channel widths.
2. *Alternate bar process* – asymmetrical movement of alternate side bars.
3. *Limited meandering* – downstream shifting of undeveloped, loosely sinuous meanders along a narrow valley.
4. *Free meandering* – meanders rising through all stages from a slightly curved channel to omega forms without any limit of horizontal migration.
5. *Incomplete meandering* – neck cut-off occurs before a meander reaches the maximum curvature.



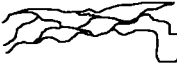









structural level	plan outline			limiting conditions
	straight	sinuous	branched	
valley bottom	 single-thread	 macromeanders	 anabranching	 wide floodplain
flood channel	 straight	 meandering	 braided (or split)	 confined channel
low water channel	 riffle-pool sequences	 alternate bars	 medial bars	 incised channel

Figure 2. Classification of river channel patterns

1a. *Channel multibranching* – corresponds to ‘classic’ braiding.

5a. *Floodplain multibranching* – corresponds to anastomosing or anabranching.

This classification was criticized by Chalov (1979, 1983), who argued that it fails to distinguish the structural levels of fluvial relief: side bars and meanders, mid-channel bars and floodplain islands are all treated as comparable forms in terms of their role in the classification. Chalov recommended three classes of relief to be defined: floodplain, channel form and bar.

Another shortcoming occurs in that limiting conditions of channel migration were given little consideration, and are only relative to the meandering process. Accordingly, Chalov (1983, 1996) proposed distinguishing *incised* rivers and rivers with wide floodplains (*wide-floodplain* rivers), transitional types of rivers with *confined* channels as well. Each of these could be subdivided as straight, meandering or branched.

Vertical deformation plays a general role in the development of incised channel patterns. Morphological features of incised rivers are determined mainly by the geological structure and history of the valley. Channels formed along folds and faults in hard rocks are rather straight. Incised meanders usually develop as a result of the intensive incision of originally sinuous rivers in relatively soft rocks. Multiple channels in this case are connected either with hard rock exposure in the river bed (structural branches) or with accumulation areas where flow capacity decreases both in valley expansions and when slope diminishes as a result of downstream changes in lithology.

As for rivers with wide floodplains, in this case stream power is the main factor in channel development. In Chalov's fluvial relief classification every main type subdivides into varieties according to the planform, the deformation tendency and the flow dynamics. Meanders subdivide into *segment-like* (downstream shifting prevails), *omega-like* (transverse development is in the order with the shifting) and *cut* (similar to incomplete meandering). Branches may be solitary and conjugate, or simple and complicated. The anabranching channel is defined as a special type, which may develop both from meandering when frequent neck cut-offs occur, and from braiding throughout vegetal colonization of bars and consequent island growth, accretion and avulsion.

Given these classification factors, the following general scheme may be suggested (Figure 2). According to this scheme every main feature (straight, meandering, branched) may be distinguished on every relief or ‘structural’ level, as was done in the information system on morphology and morphometry of Russian rivers (Alabyan, 1996).

Channel configuration in terms of the valley floor pattern may be defined either as relatively straight without

floodplain branches, or as *macromeanders* (*macrobeds*) which arise as a result of the sinuosity of the meander belt axis. Channel division on this level produces the known *anabranching* pattern.

Every anabranch as well as every segment of macromeander may be classified on three main flood channel patterns: straight, meandering and split (specifically *split* rather than *braided* because the former term is traditionally used for the case of mid-channel island division (Ferguson, 1984). The term *braided* channel is usually used for straight channels abounding with medial bars, and meandering channels with braid bars are known as *wandering*. Straight floodchannels with alternate bars are referred to by Carson (1984) as *meandertal*. *Anastomosis* is interpreted by Knighton and Nanson (1993) as branching on all levels. So every known pattern may be described as a combination of three main configurations on three main relief or structural levels. Of course, as with all natural systems there are no distinct boundaries in this two-dimensional continuum, either between planforms or relief levels, and many transitional forms can exist.

The influence of additional limiting factors may also be considered relative to the different structural levels as conditions which influence channel form. In wide floodplains, any form including macromeanders may develop. Confined channels form when the valley width is approximately equal to the width of the meander belt which in turn reflects the dominant discharge and slope. Incised rivers usually have much narrower valleys and only bars and undeveloped alluvial forms may occur. In the extreme case a non-accumulative form may exist and the channel processes consist only of bed erosion and transitional sediment transport.

### REASONS FOR PATTERN DIVERSITY

Mathematical models of different kinds offer a role in accounting for the main controls of channel formation. The most popular simulation method involves investigation of equations for flow and sediment transport in a straight channel with a low-amplitude periodic perturbation of its geometry or hydraulic conditions (Engelund and Skovgaard, 1973; Parker, 1976; Fredsoe, 1978). According to these models, flow in straight channels is unstable and relatively narrow channels are more unstable in relation to meander-like perturbations, while wide shallow channels are unstable in relation to braid-like perturbations.

Another type of simulation lies in the analysis of flow and sediment transport equations in the context of some variational hydrodynamical principle (Yang, 1976; Chang, 1979; Bettess and White, 1983). These studies conclude that a distinct value of *equilibrium slope* may be calculated. If valley slope is equal to this value the channel is rather straight, if the valley slope is greater the river may accommodate this discrepancy by meandering, but if the valley slope is too large braiding develops to decrease the water discharge in each channel. The lower the discharge, the greater the equilibrium gradient. A number of laboratory experiments (Andreev and Yaroslavtsev, 1958; Ackers and Charlton, 1970; Schumm and Khan, 1972; Bettess and White, 1983) has shown agreement with such a scheme.

In natural rivers the excessive stream power is spent on lateral or bed erosion depending on the geological structure of the valley. If bed erosion dominates, an incised channel is formed. In the case of prevalent lateral erosion, a wide floodplain is formed, and as a result of bank erosion the stream loses its stability and either meandering develops or several dynamic axes form and braiding begins.

One of the main methods of investigating natural channel patterns involves gradient–discharge chart analysis. The physical essence of this chart is that the higher and further to the right a river plots, the higher stream power it has, because a high value of both discharge and slope cause a high stream power. Practically all research of this kind has shown that meandering channels plot lower than multiple ones.

At the same time, discriminant functions for meandering and braided channels vary across a wide range. One of the main reason for this lies in differences in the operational definitions both of the slope and discharge and the channel pattern.

Romashin (1968), Carson (1984) and Ferguson (1984) were right to contend that the valley (but not the channel) gradient and the magnitude–frequency definition of discharge must be used to secure independence of the control variables. Originally the use of magnitude–frequency analysis to calculate a representative discharge was suggested by Schaffernak (1950), who investigated the water level spectrum and the product of stream power and frequency. The maximum value of this product corresponds to the effective discharge. Makkaveev (1955) and Wolman and Miller (1960) postulated that in alluvial rivers the discharge which

transports the greatest sediment in the long term is the effective (dominant or channel-forming) discharge. Practically, the effective discharge may be determined using a diagram in which values of the product of sediment discharge and frequency of occurrence are plotted against corresponding water discharge values – *the effective discharge curve*. The effective discharge has the maximum value of this product and corresponds to the maximum of the curve. According to Makkaveev, rivers of the Russian Plain usually have one or several effective values, one of which is close to the mean annual flood. This fact confirms the possibility of using the mean (or median) annual flood as the first approximation of the effective discharge when constructing discharge–slope ( $Q$ – $s$ ) diagrams.

Another important reason for discrepancy in discriminant functions lies in the different definitions of channel patterns, particularly because of the confusion of relief or structural levels, and the mixture of incised and floodplain rivers included.

## TRANSITIONS

Romashin (1968) constructed a  $Q$ – $s$  diagram using valley slope and median flood discharge for freely developing channels. His results coincide with the conclusions of Leopold and Wolman (1957) and Lane (1957) in general, but the slope of the discriminant line between meandering and multibranching rivers is more than twice as steep on this chart. This difference caused various energy-related interpretations of  $Q$ – $s$  charts.

Carson (1984) and Ferguson (1984, 1987) interpreted a gently inclined discharge–slope threshold as operating with specific stream power (power per unit of flow length and per unit width)  $\rho g Q s / w$  [ $\text{W m}^{-2}$ ] (where  $\rho$  is mass density of water,  $g$  is acceleration due to gravity, and  $w$  is flow width). According to them the meandering–braiding threshold specific power is of the order of  $30$ – $50 \text{ W m}^{-2}$ .

Analysing Romashin's diagram, Antropovskiy (1972) suggested considering stream power per unit of flow length  $\Omega = \rho g Q s$  [ $\text{W m}^{-1}$ ]. He found some  $\Omega$  thresholds between free meandering, incomplete meandering and multibranching patterns.

After re-examination of data in terms of a modern classification, the field of the diagram may be divided into three parts:

1. area of meandering (below dotted line, Figure 3A),  $\Omega < 4 \text{ kW m}^{-1}$ ;
2. area of meandering and branching,  $4 < \Omega < 15 \text{ kW m}^{-1}$ ;
3. area of branching (above solid line, Figure 3A),  $\Omega > 15 \text{ kW m}^{-1}$ .

Use of  $\Omega$  values instead of specific power seems to be appropriate for free channels because width itself depends on  $Q$  and  $s$  values in unconfined conditions.

The same steep slope exists in the discriminant lines on the  $Q$ – $s$  diagram for different bar types in the Ob river (Alabyan, 1992a; Figure 3B), which has a sandy branched channel. The tendency is the same: braid bars plot in the upper part of diagram, alternate bars and riffle–pool sequences locate below them. Comparison of transitional values for different structural levels shows a relation between flow power and channel morphology (Table I).

## EFFECTIVE DISCHARGE CURVES

The above-mentioned effective discharge curve (EDC) is an integral characteristic of hydrological and sediment regime and reflects the main features of the channel pattern. The EDC may be used for channel pattern analysis.

Every flow that transports sediment affects channel form. The product of sediment discharge and its frequency may be considered as an index of the channel-forming rate. Constructing an EDC allows conversion from solitary discharge values (mean, extreme, bankfull, etc.) to a continuous discharge spectrum (Alabyan, 1992b).

To compare EDC features with typically used  $Q$  values, several horizontal lines may be drawn, including some which correspond to certain transitions:

1. the *bankfull line* corresponds to the bankfull discharge;

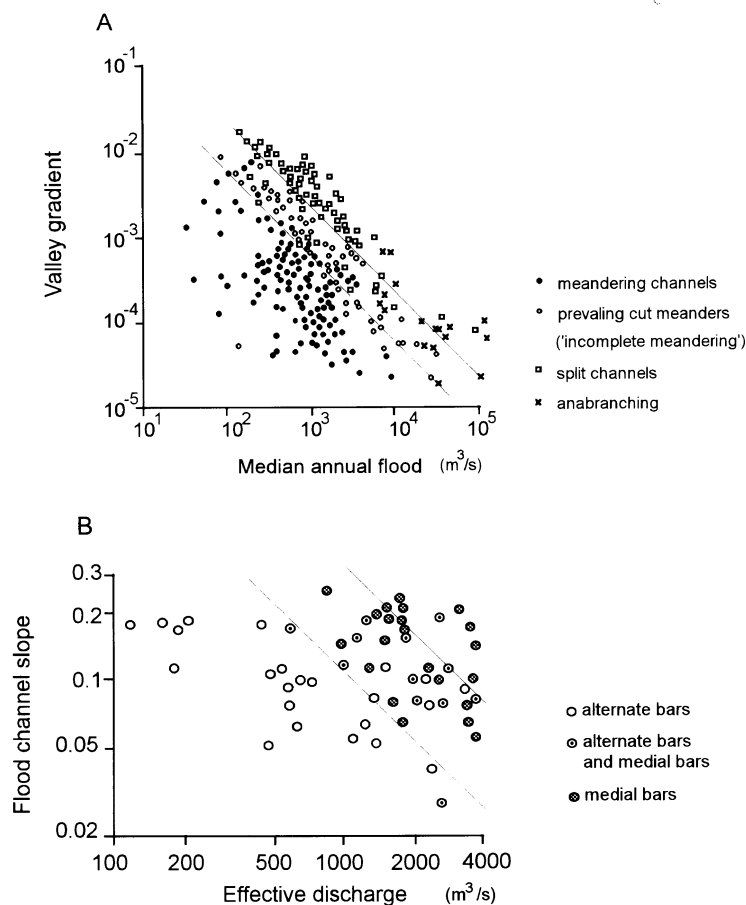


Figure 3.  $Q$ - $s$  diagrams for different structural levels of channel relief: (A) floodplain and flood channel levels (data of Romashin, 1968); (B) bar level (the Ob River)

Table I. Flow power and channel morphology

Flow power ( $\text{kW m}^{-1}$ )	Channel outline	Dominant bar type
>15	multibranching	medial bars
4–15	multibranching and meandering	medial bars
3–4	meandering	medial bars
1–3	meandering	medial bars and alternate bars
<1	meandering	alternate bars and riffle–pool sequences

- the *meandering–branching transition line* corresponds to  $\Omega=4\text{ kW m}^{-1}$  ( $\rho$ ,  $g$ ,  $s$  values are supposed to be constant);
- the *side bar–mid-bar transition line* corresponds to  $\Omega=1\text{ kW m}^{-1}$ .

Correlation of EDC elements with these three lines indicates a relationship with channel features, and may be illustrated by the following examples (Figure 4). All of these rivers are located in the West-Siberian Lowland composed of soft sedimentary rocks allowing free conditions for channel development.

The Upper Ob River has a complicated split channel, with medial bars prevailing in branches. Almost the entire EDC lies below the bankfull line (Figure 4A), so channel-forming activity is concentrated below the floodplain level. Both the high-water and low-water part of the EDC are located above the side bar–mid-bar

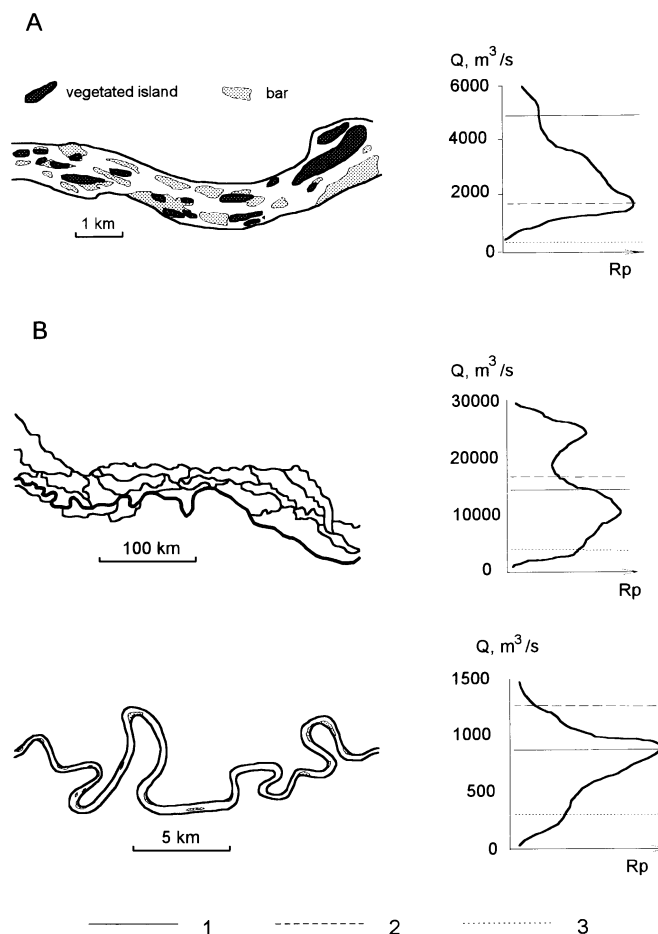


Figure 4. Channel patterns and corresponding effective discharge curves: 1, the bankfull line; 2, the meandering–branching transition line; 3, the side bar–mid-bar transition line

threshold line, so mid-channel bars may be formed during every hydrological season. The high-water part of the EDC is situated above the meandering–branching threshold line, so stream power during a flood is sufficient to form splits in the channel.

The Ob River in its lower reach is characterized by anabranching; branches are meandering with alternating bars. The upper maximum of the EDC is well encountered and located above the meandering–branching threshold line which in turn plots above the bankfull line (Figure 4B). So the power is sufficient to cause channel division only when the floodplain is inundated. Similar EDCs may be constructed for examination of any anabranch, if the discharge distribution is known throughout every hydrological phase.

The Chulym River (a tributary of the Middle Ob) has a meandering channel with alternating side bars and individual mid-bars. The meandering–branching threshold line is situated above the EDC (Figure 4C) so the channel is single-thread. Mid-bars may be formed only during a flood, but are not maintained through the low-water season.

## CONCLUSION

Every main pattern (straight, meandering, branched) may be distinguished on every structural level of fluvial relief (floodplain, flood channel, low-water channel). The composition of straight, meandering and branched features on various levels defines the channel pattern. Data analyses in the form of gradient–discharge charts constructed for channel forms of different order define a number of  $Q$ – $s$  transition criteria, which reflect stream

power per unit flow length. Using such criteria, the main problem is to choose a representative discharge value. To shift from the use of solitary values (mean, extreme, bankfull) to the continuous discharge spectrum, an effective discharge curve is constructed. This allows interpretation of multilevel channel planforms in relation to both channel and bar-scale threshold criteria.

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